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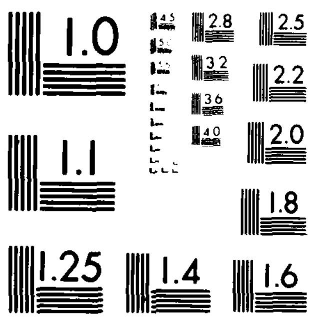

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Characteristics of a Power Line Used as a VLF Antenna

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1 May 1982

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The 100-kW Transportable Very-Low-Frequency (TVLF) transmitter system was used at Kafjord, Norway, for transmissions to the SCATHA and GEOS spacecraft. A 22-kV 10.6-km long transmission line was used as an antenna. Modifications were made in the line to reduce telephone interference. Components were designed and installed to reduce the resonant frequency and increase the antenna current. The final practical operating current was 45 amperes at 1280 Hz. This resulted in power dissipation of 72 kW and an estimated radiated power of 0.17 to 0.79 watts.

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Preface

The initial impetus to use the TVLF transmitter in Scandinavia was provided by Dr. Arne Pedersen of ESTEC. The Space Activity Division of the Royal Norwegian Council for Scientific and Industrial Research (NTNF) was particularly helpful with numerous negotiations and arrangements with Norwegian agencies. We are especially indebted to Prof. Jan A. Holtet of the University of Oslo who devoted many months helping in the field, and working with the local and national agencies to insure success in the transmissions, to Prof. Les Woolliscroft, University of Sheffield, who was able to inspire a number of agencies to help us financially, and in addition, made the ground calibration measurements for the 1980 campaign and to R. G. Robbins, R. L. Walter, and J. Dohl who worked hard to overcome the equipment failures and keep the transmitter on the air. We wish to thank Prof. M. Garnier, G. Girolomi and J. Conrad, University of Paris, who made measurements and transmissions which were helpful in designing components for the TVLF transmitter, and demonstrated a transmission line configuration that would not cause telephone interference. We also wish to thank R. Barr, DSIR New Zealand, for a copy of his program for computing line impedances.

This work was supported in part by the National Science Foundation under Grants ATM77-19361 and ATM80-19060 and in part by the U. S. Air Force System Command, Space Division under Contract F04701-80-C-0081.

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Background

Attention in the Space Science community has recently been directed toward possible effects of power-line harmonic radiation on the Earth's radiation belts (Helliwell et al., 1975; Park and Helliwell, 1978; Thorne and Tsurutani, 1979). The members of the GEOS S-300 Experiment Scientific Board proposed using power transmission lines for antennas in a program to transmit ELF signals to the GEOS satellite. Since The Aerospace Corporation also provided a VLF receiver for the P78-2 (SCATHA) satellite this provided a unique opportunity to study power line radiation, wave-particle interactions and whistler-mode propagation in the outer magnetosphere.

The measurements reported here were undertaken to understand the technical aspects of ELF/VLF radiation from an actual power line over a ground whose effective conductivity is a function of frequency. A 60-kV line was made available for tests at Andoya, Norway. Impedance measurements indicated that the line would be satisfactory as an antenna. However local residents experienced troubles with appliances which were being serviced temporarily with a 22-kV backup line. A 60-kV line, which did not require customers to receive service from an inferior line, was located in Konstadbotn, Norway. Preliminary transmissions were made using the 100-kW TVLF transmitter (Koons and Dazey, 1974) running at currents as high as 50 amperes. Severe telephone interference was experienced which was attributed to the fact that the line ran within a few hundred meters of a fjord, and most of the telephone subscribers had residences between the line and the fjord.

A third line, approximately 15 km long, was located in a remote part of Norway about 300 km from Tromso near the town of Kafjord. There were a few telephone subscribers near the Kafjord end of the line. Low-level tests indicated serious telephone interference in the nearby residences. Since the residences were all close to the transmitter end of the line, a test was made with the first 3.6 km of the line 'floating' above ground with the current being inserted into the ground at the 3.6-km point. Tests with subscribers and the telephone switchboard indicated that currents considerably above 50 amperes could be used without causing interference in the telephone system.

In this paper we describe the electrical characteristics of the Kafjord power line when used as a VLF antenna. The Kafjord line runs 14 km up a mountain from sea level to 800 m between Kafjorddalen and Lake Guolasjav'ri in Troms Province, North Norway.

The Operating Mode of Transmission Line Antennas

In the simplest configuration a transmission-line antenna can be considered a rectangular-loop antenna with current going out on the transmission line wires, going to ground at the far end, and returning in the ground back to the low potential side of the transmitter (Burrows, 1978). When VLF currents travel in the ground they penetrate large distances because of the large skin depth at the low frequencies involved. In its simplest form the area of the loop antenna at the frequency of interest is approximately the product of the length of the transmission line and the skin depth divided by the square root of two.

An early concept of a transmission line antenna was the Beverage antenna. This antenna utilized a terminating resistor as a load at the far end of a long wire to avoid detuning and the high voltages which could result from resonances. However, if the line insulators can tolerate the high voltages, more current can be obtained by operating the line at a resonant frequency. This technique also eliminates the terminating resistor as a source of power loss.

In the interest of safety and ease of design high-power transmitters are usually operated with a low output impedance, i.e., at high currents and relatively low voltages. A transmission line a quarter of a wavelength long with an open circuit at the far end provides a low impedance for a transmitter and is the preferred operating mode.

Since VLF currents in the ground flow in a cross section of dimensions proportional to skin depth they encounter a resistance per unit length, R_e/m, which is independent of the earth resistivity and is only a function of frequency, f. From our measurements the resistance value is about $= 10^{-6} \times f$ ohms/meter where f is the frequency in Hertz.

In addition to the resistance described above, there is an added resistance when ground stakes are used to connect the low potential side of the TVLF system to the earth. This resistance is caused by current concentrations near the stakes and is a function of earth resistance, the number of stakes used and their placement. For simplicity we assume that the ground insertion resistance is independent of frequency. Based on our measurements, the value can be as low as a few ohms or as high as 100 ohms. An advantage of a quarter-wave open-circuit antenna is that only one connection to the earth is necessary.

In general, when a transmission line is provided, the quarter-wave resonance does not occur at a desired frequency. For transmissions to the SCATHA and GEOS satellites the desired frequency was about 1300 Hz, based upon the expected electron gyrofrequency at the location of the spacecraft. We find the typical propagation velocity in transmission line antennas to be about 0.7

times the speed of light for the lines measured in North Norway. The desired length of a transmission line for quarter-wave resonance is then 40 km.

As a practical matter, it is difficult to arrange the use of power transmission lines because of power company constraints, and the lines that have been made available are usually shorter than 40 km. The shorter lines may be electrically lengthened by adding the proper components.

In the 1979 campaign, the Kafjord line was lengthened by adding capacitors at the far end. There were severe voltage, frequency and current requirements for the capacitors. However, special units were obtained that functioned satisfactorily. The capacitor current had to be re-inserted into the earth, requiring a second grounding connection. The capacitor ground connection was made in inhospitable terrain and added considerable series resistance to the complete system.

In the 1980 campaign, a special inductor was constructed at the TVLF transmitter site and connected in series with the transmission line achieving the necessary reduction in resonant frequency with minimal increase in circuit resistance.

Details and performance results of the TVLF power line antenna combination are discussed below.

Electrical Characteristics of the Kafjord Line

It is desirable to determine the electrical parameters of transmission lines being considered for VLF antennas for a number of important reasons. The design of the tuning elements, if necessary, must be based upon the expected impedance of the line and the desired operating levels of voltage and current. The series resistance, R_s, determines how much antenna current can be supplied by a power amplifier with a given amount of power and a known output impedance. The characteristic impedance is related to the skin depth in the earth and estimates of this parameter allows one to determine the expected radiated power.

Figure 1 illustrates schematically three of the Kafjord, Norway transmission-line antenna configurations. Note that in all three cases 3.6 km of elevated line was used to transmit the power to the 10.6 km of line which was the actual antenna. Impedance measurements were made in all three configurations and estimates of inductance per meter, capacitance per meter, characteristic impedance, velocity of propagation, skin depth in the earth, and earth resistivity were made as a function of frequency.

Impedance measurements were made with a Hewlett Packard Model 3580 Spectrum Analyzer. A diagram of the measurement system is shown in Figure 2. The tracking oscillator output of the spectrum analyzer was amplified and connected to the transmission line and the Y-axis input to the analyzer through a 20,000-ohm resistor. Traces were made on an X-Y recorder. Amplitude calibrations were obtained by substituting a decade resistance box for the transmission line and plotting known impedance levels.

Provisions were made by the power company to allow access to the line at the Kafjorddalen end, and to provide an open or short circuit termination upon request at the Lake Goulasjav'ri end.

The basic data obtained in the measurements were the open and short circuit impedance (Z_{oc}, Z_{sc}) versus frequency over the range from 1 to 20 kHz. The measurement technique provides the modulus of the impedance rather than the reactive and resistive terms, although at maxima and minima in the curves one can assume the impedance is purely resistive. The skin depth varies

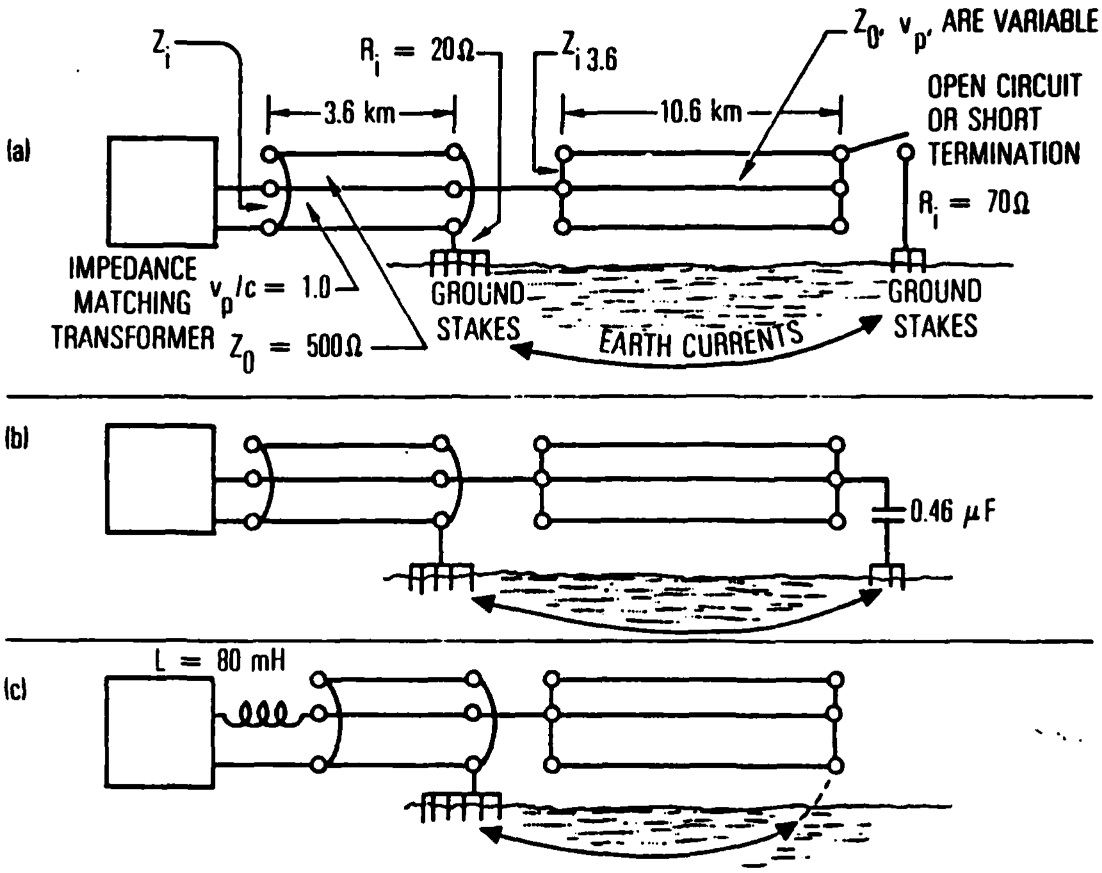

Fig. 1. Configurations of the Kafjord line; (a) Test configuration, resonant frequency = 3.8 kHz, (b) capacitive tuning, resonant frequency = 1.3 kHz, (c) inductive tuning, resonant frequency = 1.3 kHz.

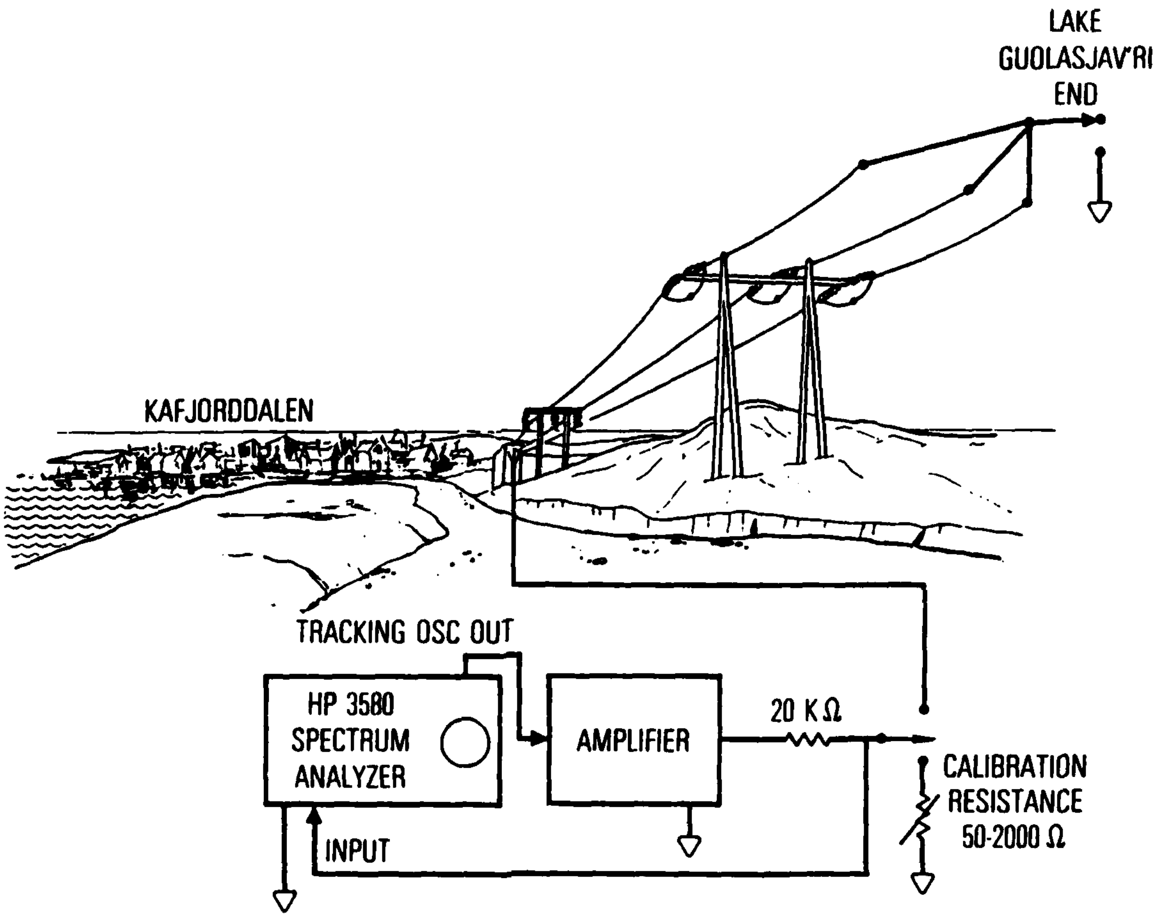

Fig. 2. Schematic of the impedance measuring system.

significantly with frequency and this causes significant changes in the characteristic impedance and the velocity of propagation. Since the total line included a 3.6-km portion with fixed impedances it appeared that there were too many variables to achieve an analytical solution. Trial-and-error curve fitting methods were adopted.

The measured short-circuit and open-circuit impedance curves for the Kafjord line are shown in Figures 3 and 4. The analytical expressions for the short-circuit and open-circuit transmission lines are shown below.

The general transmission line formula is:

$$Z_i = \frac{Z_o\,(Z_L \cosh\theta + Z_o \sinh\theta)}{Z_o \cosh\theta + Z_L \sinh\theta} \tag{1}$$

where Z_i = input impedance of the line

Z_o = characteristic impedance of the line

Z_L = load impedance at the end of the line

θ = $2\pi\ell/[(v_p/c)\lambda]$ = electrical length of line at the frequency of interest

v_p = wave phase velocity

c = speed of light

λ = free space wavelength.

For Figure 1a, Z_L = 70 ohms for the short-circuit case and infinity for the open-circuit case.

Equation (1) above is complex, since both Z_o and θ are complex. The relationship with physical properties are as follows:

$Z_o = [(R + j\omega L)/(G + j\omega C)]^{1/2}$

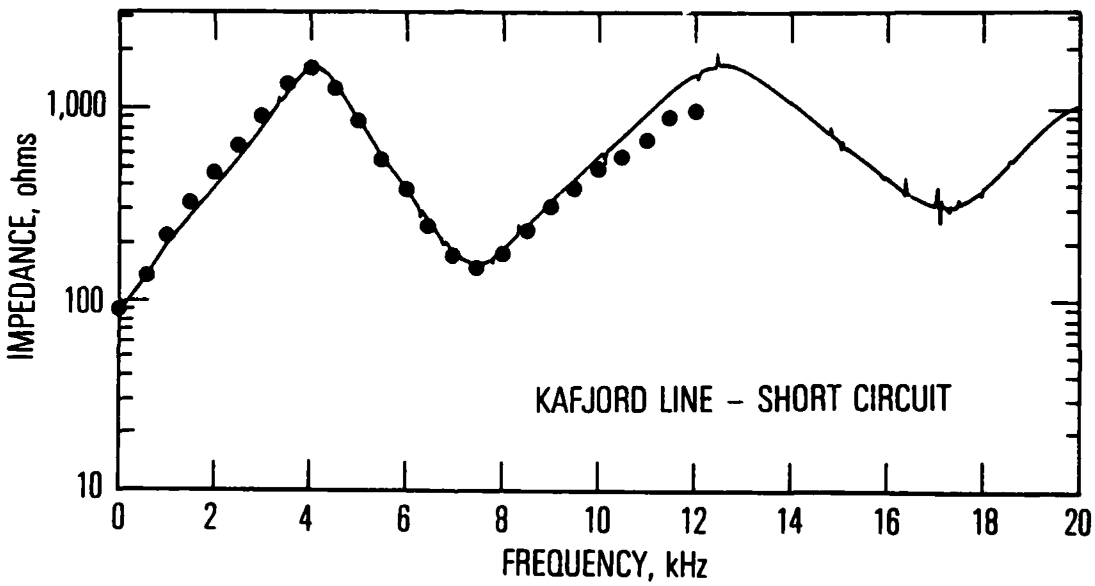

Fig. 3. Short-circuit impedance of the Kafjord line.

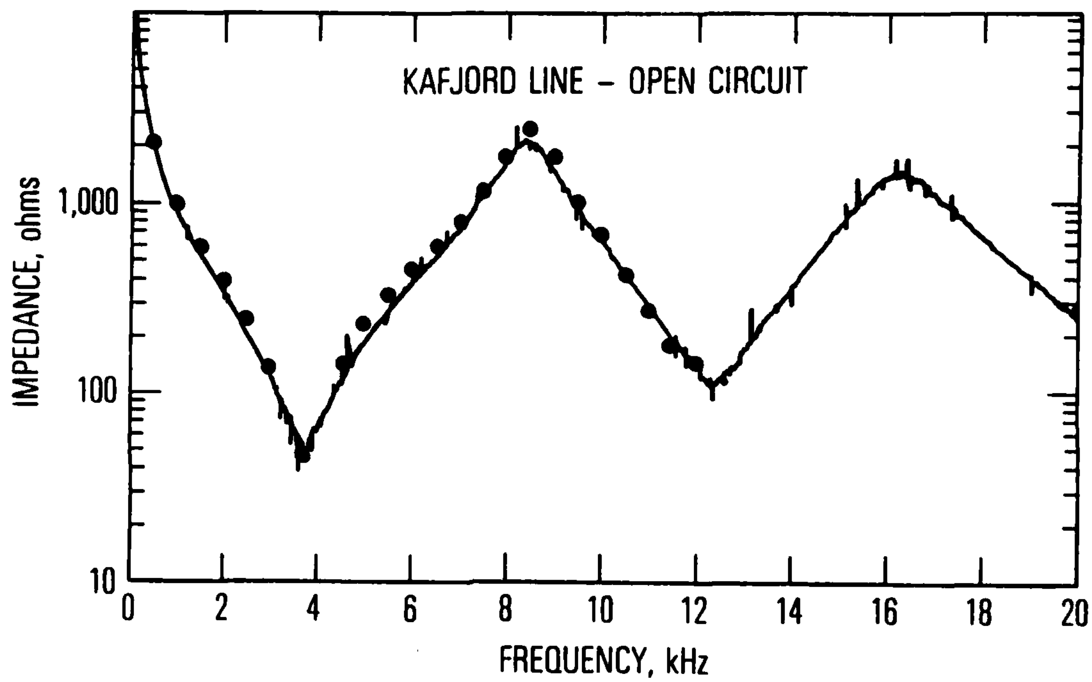

Fig. 4. Open-circuit impedance of the Kafjord line.

$$\theta = \ell[(R + j\omega L) \times (G + j\omega C)]^{1/2} = \text{propagation const.} \times \text{line length}$$

where:

ω = 2 π × frequency (Hz)

ℓ = physical length of line, meters

R = Resistance/meter of line

L = Inductance/meter

G = Conductance/meter

C = Capacitance/meter.

An estimate, based on measurements and curve fitting indicate the following values for Z_o and θ at 4000 Hz:

$Z_o = 383(1 - 0.0427\ j)$ ohms

$\theta/\ell = \omega \times 4.865 \times 10^{-9}\ (0.0427 + j)$ radians/meter

The reciprocal of 4.865×10^{-9} is 2.05×10^{-8} meters/second, which indicates a propagation velocity of .685 times the free space velocity.

The input impedance of the 10.6-km section of the line, that is the impedance looking into the line at the 3.6 km point assuming a zero resistance ground terminal, is given by inserting the proper values into the general expression for the input impedance of a transmission line. If we call this value $Z_{13.6}$ and add to it the 20-ohm resistance estimated for the ground rods at the 3.6-km point, we have a load resistance for the 3.6-km section of the line which is given by

$$Z_L = Z_{13.6} + 20 \qquad (2)$$

If this Z_L is substituted into the general transmission line formula, together with the new electrical lengths and characteristic impedance, 500 ohms for the 3.6-km line, we obtain the input impedances at the transmitter end of the Kafjord line. Since most of the values are complex, the input impedance is complex. Therefore the total magnitude, or modulus, must be obtained for comparison.

The transmission line expressions were programmed on a Texas Instruments, TI 59, calculator. The assumptions and procedures used for the trial and error fitting were as follows:

1. The earth resistance was assumed to be given by $R_e/m = 10^{-6} \times f$ ohms/meter.
2. The value of the insertion resistance, 20 Ω, at the 3.6-km point was estimated from the first minimum of the open circuit impedance curve by subtracting the earth resistance.
3. The value of the insertion resistance, 70 Ω, at the short circuit, or far end of the line, was estimated from a somewhat risky extrapolation of the short circuit impedance to zero frequency, and subtracting the insertion resistance at the 3.6-km point.
4. The 3.6-km section of line was assumed, based on wire diameter and spacing, to have a constant characteristic impedance of 500 ohms and a propagation velocity of 1.0, with negligible resistance.
5. Estimates were made of Z_o and v_p in the region of 4 and 8 kHz, the frequencies of resonances and anti-resonances in the short circuit and open circuit cases. In general, the low impedances represent essentially the series resistance, R_s, of all elements, as modified by the 3.6-km section of line. The high impedance represents the value of:

$$Z_i = Z_o^2/R_s \tag{3}$$

which is mainly dominated by the value of Z_o. The location of the minima and maxima are determined by v_p.

6. Values of Z_o and v_p were tried until good fits to the experimental curves were obtained. That is, the maxima and minima had proper magnitudes and frequencies. This was done at 4 kHz, and repeated at 8 kHz.

7. The distributed inductance per unit lenth, L, and the capacitance per unit length, C, were then determined from:

$$L = Z_o/v_p \quad \text{Henrys/meter} \tag{4}$$

$$C = 1/Z_o v_p \quad \text{Farads/meter} \tag{5}$$

The results from the above assumptions and the curve fitting are shown in Table 1 and plotted as solid circles in Figs. 3 and 4. The calculated values of the capacitance increased and inductance decreased with frequency, as expected, since the ground currents flow closer to the conductor as the frequency is increased. The experimental data is not sufficiently sensitive to provide the functional relationship between inductance, capacitance, and frequency, so a linear relationship was assumed.

From L and C, we can calculate Z_o and v_p as a function of frequency from:

$$Z_o = (L/C)^{1/2} \tag{6}$$

and

$$v_p = 1/(LC)^{1/2} \tag{7}$$

Table 1. Kafjord line impedance parameters. Here f is the signal frequency in hertz.

Parameter	Value
Distributed Inductance, Henrys/meter	$2.16 \times 10^{-6} - 7.5 \times 10^{-11} f$
Distributed Capacitance, Farads/meter	$1.13 \times 10^{-11} + 3.5 \times 10^{-16} f$
Insertion Resistance at transmitter end, ohms	20
Insertion Resistance at far end, ohms	70

Curves showing the variation of Z_o and v_p with frequency, as calculated from the expressions above are shown in Fig. 5.

Capacitive Tuning of the Kafjord Line

The Kafjord line resonated at approximately 3.8 kHz in the quarter-wave open-circuit mode. Operational requirements made it necessary to operate at 1.3 kHz, and in 1979 this frequency was obtained by adding capacitors to the far end of the line.

Simple trigonometric expressions are usually adequate for estimating the value of the capacitance required and the expected losses. Based upon earlier measurements, it was assumed that the line would have a characteristic impedance of about 350 ohms (somewhat less than the 417 ohms obtained from the results presented in Fig. 4), and a velocity of propagation of about 0.7 c.

The impedance of a short circuit line when measured at the open circuit end is given by:

$$Z_{oc} = j\, Z_o \tan\theta \qquad (8)$$

For the Kafjord line at 1300 Hz $\theta = 31.6°$.

Since the above value is inductive, the line can be 'tuned' with a capacitor with the same numerical value of reactance $X_c = 215\ \Omega$ or $C = 5.6 \times 10^{-7}$ farads.

Operating high voltage, high current capacitors at any other frequency than 60 Hz requires special considerations. It was possible to obtain capacitors with the standard loss factor rating, a series conductor resistance

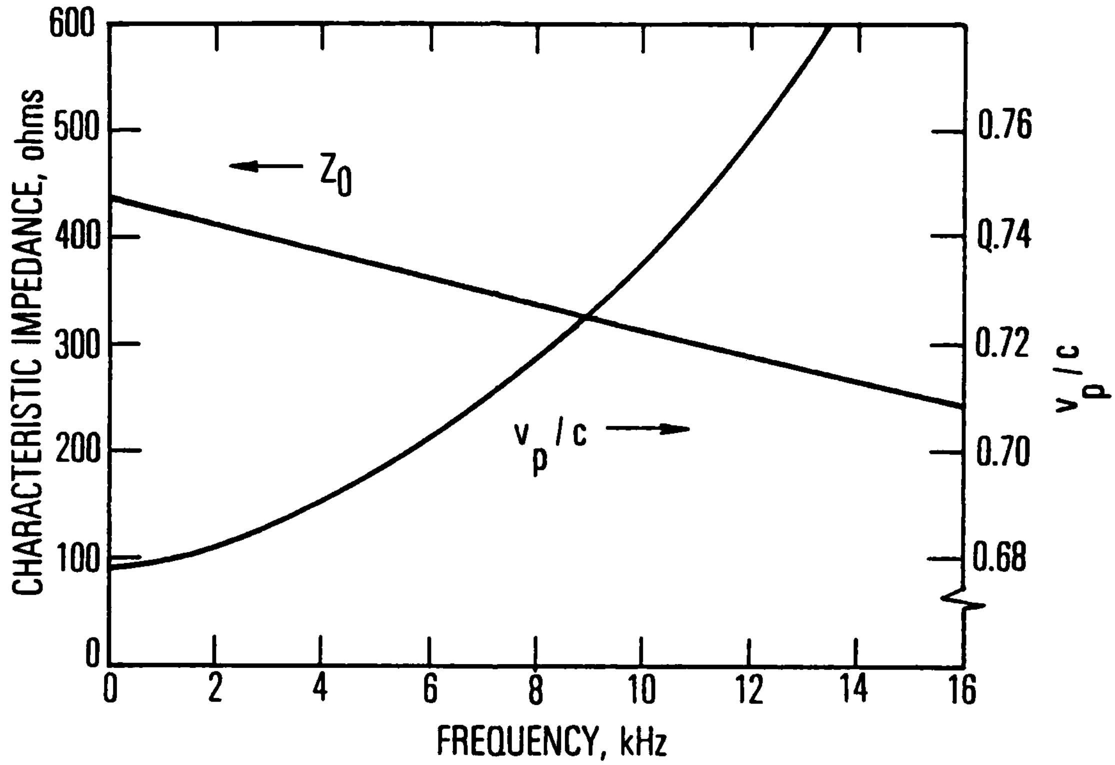

Fig. 5. Characteristic impedance, Z_o, and the ratio of the wave phase velocity to the speed of light, v_p/c.

rating, and a wattage rating. From the specifications it was possible to determine an array of capacitors which could be used, although not at the maximum power desired. The capacitor specifications are given in Table 2. It was estimated that at 1.3 kHz, the total capacitor current would be 35 amperes for an input current of 40 amperes from the TVLF system. The total voltage at the capacitors would then be 8,000 volts.

Twenty capacitors were purchased and pairs were connected in series, then ten pairs were connected in parallel, so the voltage on each capacitor was divided in 1/2 and the current was divided by 10. The losses could then be calculated for each capacitor as follows:

$$\text{Dielectric Loss} = \text{Power factor} \times \text{voltage} \times \text{current}$$

$$= .001 \times 4{,}000 \times 3.5 = 14 \text{ watts} \tag{9}$$

$$\text{Conduction Loss} = (\text{Current})^2 \times \text{conductor resistance}$$

$$= (3.5)^2 \times 0.25 = 3 \text{ watts} \tag{10}$$

for a total of 17 watts. Since the capacitors were only rated for 10 watts, care was taken to operate at less than 60% duty cycle. The wattage rating is based on a 40° C temperature rise. The location of the capacitors on the top of a mountain where there was a steady cold breeze would probably have allowed a 100% duty cycle without much danger of overheating.

The equivalent series resistance of the capacitors was:

$$R = P/I^2 = 1.4 \text{ ohms.} \tag{11}$$

The net resistance for the series-parallel array was about 0.3 ohms, which was negligible compared to the earth insertion resistance.

Table 2. Capacitors used to tune the Kafjord line to 1.3 kHz

Parameter	Value
Capacitance, μF	0.1
Voltage rating, kV	13.
Power factor	0.001
Conductor resistance, ohms	0.25
Power dissipation, W	10.
Total Capacitance, μF	0.56

Figure 6 shows the impedance vs frequency curve with 0.46 μF capacitance. The minimum impedance at resonance, i.e., the total series resistance, is the parameter that determines the antenna current possible with a given amount of transmitter power. The allocation of resistance is shown in Table 3.

Since all the current in the line does not go through the capacitors, the apparent resistance is somewhat less than the 70 ohms determined as described in the previous section. The current which does not go through the capacitors is returned to the earth as displacement current along the length of the line.

Inductive Tuning of the Kafjord Line

If an inductor is placed between the transmitter and the transmission line, the resonant frequency will be reduced. If we take the same frequencies as in the previous section we may determine the value for this inductance.

The impedance of an open circuit line is given by:

$$Z_i = -Z_o \cot \theta \tag{12}$$

Z_i is -569 Ω for the Kafjord line at 1300 Hz. Since this is capacitative, this may be tuned by an inductance with the same reactance. The value of this inductance is ~ 0.070 henrys.

Typical inductors have high losses at high frequency because the conductors are immersed in their own alternating magnetic field causing eddy currents. The large equivalent series resistance may be reduced by using an 'open' construction at the expense of increasing the length, spacing and size of the conductors. The final inductor design was based upon formulas and

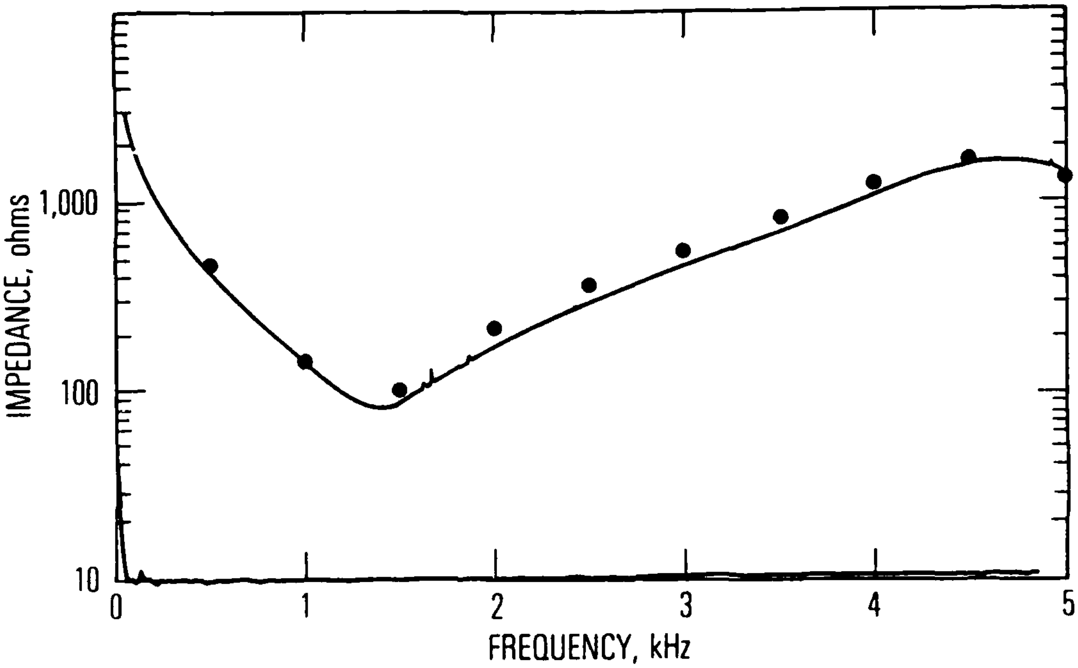

Fig. 6. Impedance of the Kafjord line tuned by 0.46 μF capacitance in series with the line to ground at the far end of the line from the transmitter.

Table 3. Allocation of the Series Resistance for the Capacitively Tuned Line

Insertion Resistance at 3.6 km	= 20 Ω
Ground Transmission Resistance	= 14 Ω
Insertion Resistance at Capacitors	= 50 Ω
Total	= 84 Ω

tables in Grover (1946) and Terman (1943). The physical and measured electrical parameters of the inductor are given in Table 4. The measured results were within reasonable agreement with the calculated values.

A 50-foot roll of soft copper tubing was sufficient for each layer. Tubes were soft soldered using a butt joint. Spacers were glass melamine. Assemblies of 12 layers were fabricated at El Segundo, CA and shipped by air to Tromso, Norway for final assembly of the full 120 layers at the site of the TVLF transmitter.

Figure 7 shows a "Q" curve obtained from the inductor. Figure 8 shows impedance curves of the line alone, the inductor alone, and the line with the inductor installed. Note that the series resistance was lowered to 45 ohms with inductive tuning, as compared with 84 ohms with capacitive tuning. The lower resistance allows currents as high as 47 amperes for the 100-kW transmitter.

Comparison of Measured With Model Impedances

Barr (1979) has presented a computational method for the evaluation of the characteristic impedance, propagation constant and open- and short-circuit input impedances of an assembly of N parallel lossy conductors of circular cross-section above an imperfectly conducting ground plane.

We have evaluated Barr's model for the electrical properties of the Kafjord line given in Table 5. The impedance of the antenna must be transformed to the impedance at the transmitter site where the impedance was measured. This was accomplished using Eq. (1) by assuming that the 3.6-km section that was operated as a transmission line (see Fig. 1) had a characteristic impedance Z_o of 500 ohms and a phase angle at the antenna given by $\theta = 4.62 \times 10^{-3} \times f$ deg where f is the signal frequency.

Table 4. Characteristics of the inductor used to tune the Kafjord line to 1280 kHz.

Parameter	Value
Turns	600
Turns/layer	5
Outside diameter, inches	36
Height, inches	120
Horizontal turn spacing, inches	1
Layer spacing, inches	1
Conductor diameter, inches	0.25
Inductance, Henrys	0.078
Resonant bandwidth, Hertz	15.4
Q	82.8
Series Resistance, ohms	7.5

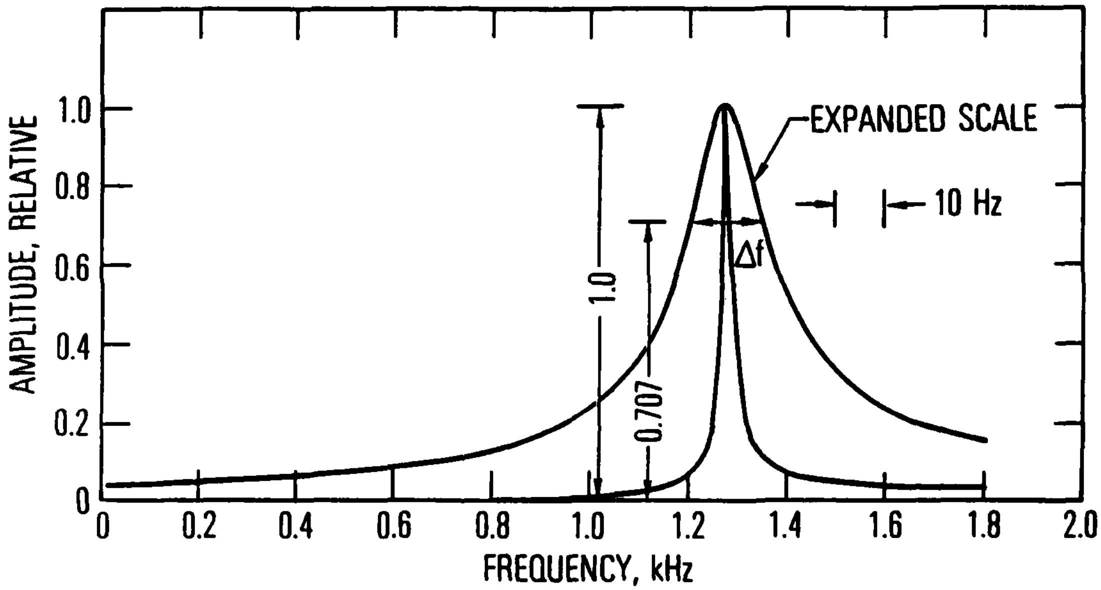

Fig. 7. "Q" curve of the Kafjord line tuned by a 70 mH inductor in series with the line at the transmitter end of the line.

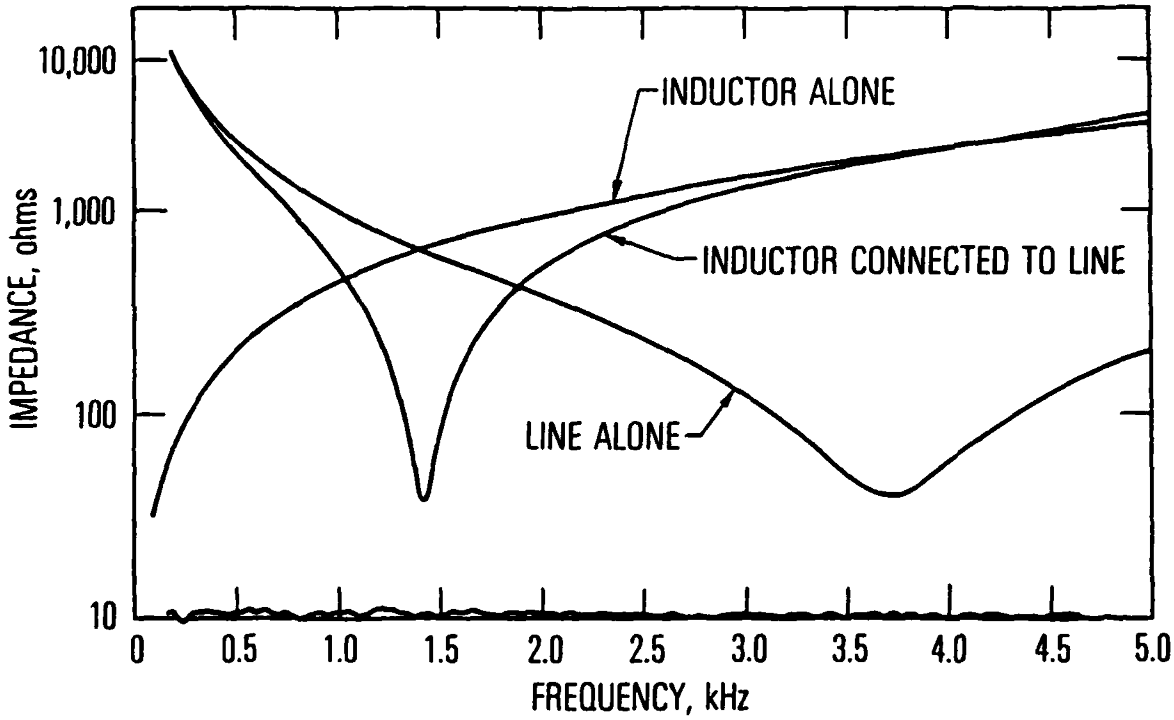

Fig. 8. Impedance of the tuning inductor and the Kafjord line in the indicated configurations.

Table 5. Physical properties and parameters used to compute the power radiated by the Kafjord line at 1280 Hz.

Parameter	Value
Wire diameter, meters	0.0087
Wire spacing, meters	1.5
Line length, meters	10,600
Skin depth, meters	4,860
Ionospheric height, meters	80,000
Wavelength, meters	234,000
Magnetic induction, Tesla	3.1×10^{-14}
Distance to receiver, meters	1.65×10^{5}
Wave phase velocity, $v_{p/c}$	0.68
Angle to receiver, ϕ, deg	40
Attenuation, nepers/m	3.5×10^{-6}

The open- and short-circuit impedances were computed for ground conductivities ranging from 10^{-4} to 5×10^{-3} S/m. The most sensitive parameter for a comparison of these model calculations with the measured impedance is the frequency of the first minimum in the open-circuit impedance. The frequency of the first minimum is plotted as a function of ground conductivity in Fig. 9. In 1979 and 1980 six impedance curves were plotted in this configuration. The average value of the frequency of the first minimum is 3729 ± 62 Hz. This frequency corresponds with a ground conductivity of 3×10^{-4} S/m. Impedance values computed from the model are plotted with the experimental curve in Fig. 10. The agreement is very good at the lower frequencies.

Radiated Power

Magnetic induction measurements were made by University of Sheffield personnel at Lavangsdalen, Norway and Kiruna, Sweden during the 1980 campaign. The measurements at Kiruna, a distance of 165 km from Kafjord, will be used here to estimate the radiated power P_{rad} using the following expressions delivered from equations 2a and 6 in Bernstein et al. (1974):

$$P_{rad} = (\omega I \ell)^2 / 8\, c^2\, \sigma_e\, h \tag{13}$$

$$= \frac{H_\phi^2\, r_e \sin(\rho/r_e)}{8\, c^2\, \sigma_e\, h\, m^2\, E^2 \cos^2\phi \exp(-2\,\alpha\,\rho)} \tag{14}$$

where

$$m = (\pi\, \mu_o/c)^{1/2}/4\pi\, \eta_o \tag{15}$$

and

$$E = [h\, (\sigma_e/c\, v_p)^{1/2}]^{-1}. \tag{16}$$

In the above equations

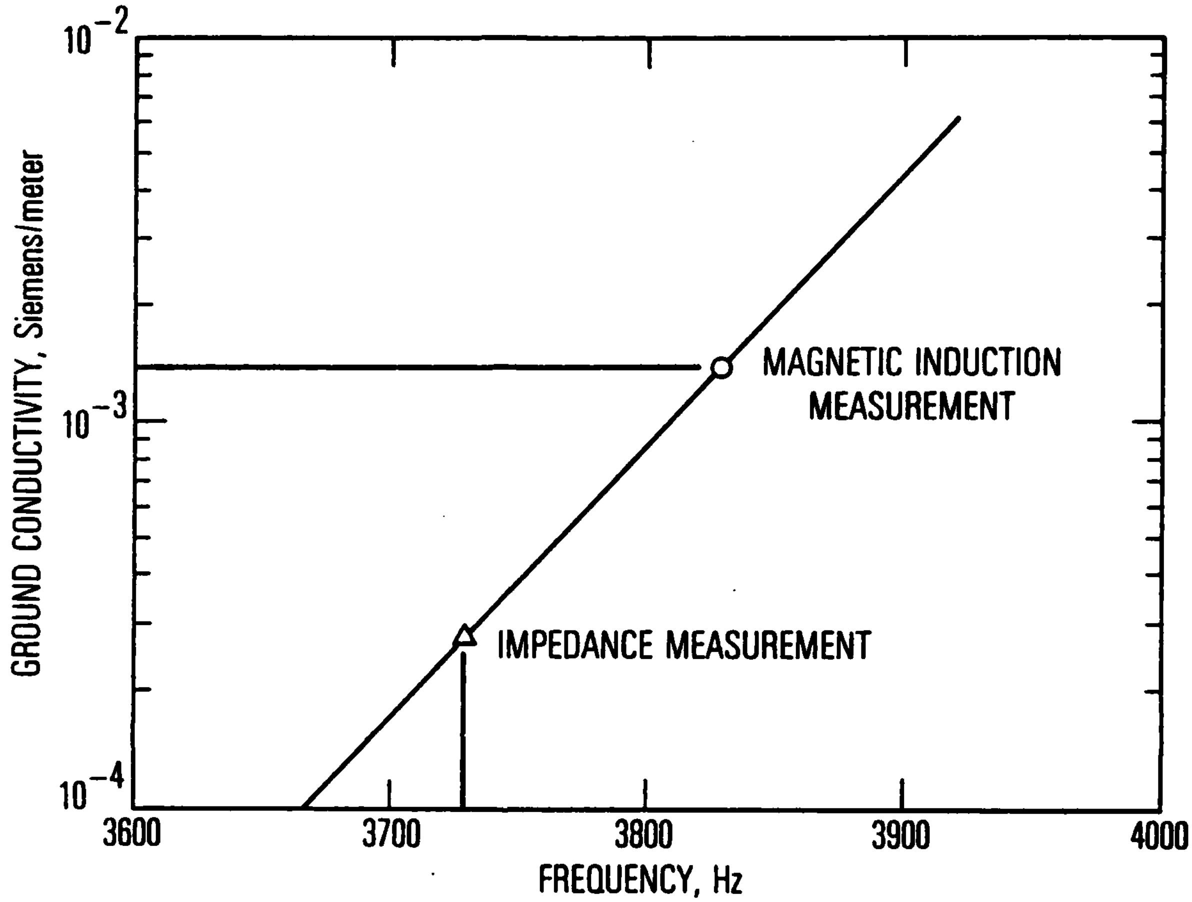

Fig. 9. Ground conductivity as a function of the frequency of the first minimum of the open-circuit impedance of the Kafjord line as computed using Barr's formulation for the line impedance. The triangle shows the frequency determined from the impedance measurements. The circle corresponds with the conductivity determined from the field measurements near Kiruna.

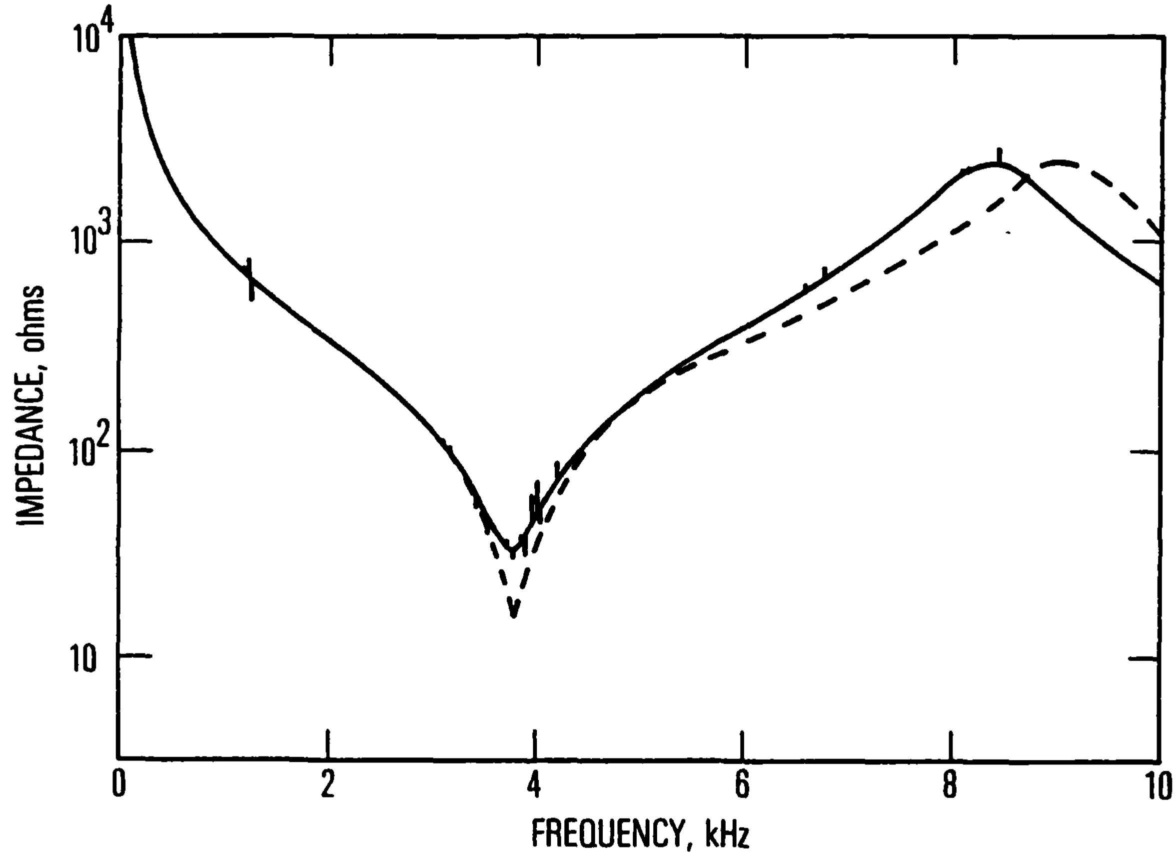

Fig. 10. A comparison of the measured open-circuit impedance of the Kafjord line (solid curve) with the open-circuit impedance computed using Barr's program (dashed curve).

ω = signal angular frequency

I = r.m.s. antenna current

ℓ = antenna length

c = speed of light

σ_e = effective ground conductivity

h = height of ionosphere

H_ϕ = magnetic intensity

r_e = radius of earth

ρ = distance between transmitter and receiver

ϕ = angle between antenna axis and receiver direction

α = earth-ionosphere waveguide attenuation

μ_o = vacuum permeability

η_g = wave impedance

v_p = wave phase velocity.

At a time when the r.m.s. antenna current was 45 A the magnetic induction, $B_\phi = \mu_o H_\phi$, measured near Kiruna, Sweden was 3.1×10^{-14} T (L. Woolliscroft, private communication).

Incorporating Eqs. (15) and (16) into (14) and expressing the result in terms of B_ϕ we get:

$$P_{rad} = \frac{2\pi\, c^2\, B_\phi^2\, h\, r_e \sin(\rho/r_e)}{\mu_o\, v_p \cos^2\phi \exp(-2\alpha\rho)} \tag{18}$$

Note that this result is independent of the effective ground conductivity.

At 1280 Hz the signal is strongly attenuated in the earth-ionosphere waveguide. We adopt an attenuation of 30 dB/Mm or 3.5×10^{-6} nepers/m from Figure 3 of Bernstein et al. (1974).

The values in Table 5 substituted into Eq. (18) give a radiated power of 0.168 W. The earth's conductivity calculated from Eq. (13) using this value for the radiated power and the line parameters in Table 5 is then 1.4×10^{-3} S/m. This value is a factor of 4.7 higher than that obtained from the line impedance measurements described in the previous section. Since both results are model dependent this discrepancy is not surprising. The radiated power computed using Eq. (13) and the lower conductivity obtained from the impedance measurements is 0.79 W. This is probably an upper bound with the actual value closer to the 0.17 W obtained from the magnetic induction measurements.

This low value for the radiated power was sufficient to occasionally stimulate plasma wave emissions in the outer magnetosphere. Plasma wave measurements from the high altitude GEOS-2 and SCATHA satellites near the Kafjord, Norway magnetic meridian during VLF wave-injection experiments are reported by Garnier et al. (1981).

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